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Effect of Welding Speed on Mechanical Properties of Dissimilar Friction Stir Welded AA5083-H321 and AA6061-T6 Aluminum Alloys

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***Abstract*— *Fusion welding of aluminum and its alloys tends to degrade the mechanical strength at the weld joint area due to high thermal diffusivity and high melting point. Friction Stir Welding (FSW) is the best alternative for joining of these materials against fusion joining. FSW is an emerging solid state joining process in which the material that is being welded does not melt and recast. The main objective of this research is to use FSW for joining of 5 mm thick AA5083-H321 and AA6061 T6 aluminum alloys using taper cylindrical threaded tool pin profile and scrolling on shoulder surface. The microstructure and mechanical characterization of dissimilar friction stir welded AA5083-H321 and AA6061-T6 aluminum alloys were studied. Four different welding speeds (40, 63, 80 and 100 mm/min) were used to weld the dissimilar alloys at constant tool rotational speed of 1120 rpm, tilt angle 2.5^0. The effect of welding speed on metallurgical and mechanical properties was analyzed. It is found that the welding speed of 80 mm/min produces good mechanical and metallurgical properties than other welding speeds. The observed results were correlated with the fracture features and microstructure. The fracture mode was observed to be a ductile fibrous fracture.*

Keywords*— *AA5083-H321 and AA6061-T6 aluminum alloys, friction stir welding, welding speed, tensile strength, microstructure, Fractography.

I. INTRODUCTION

Dissimilar welding of aluminum alloys AA5xxx and AA6xxx is regularly faced in the manufacture of aircraft structures and other auxiliary applications [1]. Various welding defects happen in conventional fusion welding of aluminum alloys such as hot cracking, voids, distortion, loss of work hardening, lack of penetration, precipitate dissolution and hot cracking in the joints [2]. Therefore, Friction stir welding technique is preferred to solve those defects. Friction stir welding (FSW) is a suitable solid state welding procedure to successfully join any combination of dissimilar aluminum alloys [3]. FSW was developed at The Welding Institute (TWI), UK in 1991. A non-consumable rotating tool harder than the parent material is plunged into the abutting edges of the plates to be joined under adequate axial force and progressed along the line of the joint. The tool consists of two parts, in particular pin and shoulder. The material around the tool pin is softened by the frictional heat produced by the tool rotation. Progression of the tool pushes plastically deformed material from front to back of the tool and forges to complete the joining process [4]. Since FSW is a solid state method, a solidification structure is not visible in the weld. In this way, all the defects related to the presence of the eutectic phases and brittle inter-dendritic are wiped out [5]. A few reviews on FSW of dissimilar AA6xxx and AA5xxx joints were recently described in Refs. [6_10]. LEAL et al [6] investigated the impact of tool shoulder geometry on material flow in 1 mm-thick AA6016-T4 and AA5182-H111 joints. A tool shoulder with a conical cavity was given to yield an onion ring structure. PARK et al [7] elaborated the influence of material locations on the properties of 2 mm-thick AA6061-T6 and AA5052-H32 joints and a proper mixing of dissimilar aluminum alloys was seen when AA5052-H32 was kept in the advancing side. PEEL et al [8] concentrated the impacts of tool rotational speed and traverse speed on the hardness, microstructure and precipitation distribution of 3 mm-thick AA6082and AA5083 joints. STEUWER et al [9] measured the impact of traverse speed and tool rotational speed on the residual stresses of 3 mm-thick AA6082 and AA5083 joints. ELANGOVAN and BALASUBRAMANIAN [10] announced that the welding speed has a more prominent impact on the tensile strength. YAN et al [11] concentrated the dissimilar friction stir welding between AZ31 and AA5052 magnesium alloy and revealed that at the highest point of the mixing zone, AZ31 and AA5052 alloys are simply bonded, while onion ring structure which consisted of magnesium bands and aluminum

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bands is formed at the bottom of the stir zone. The microstructural development of dissimilar welds as a function of processing parameters has been widely studied to discover the behavior of AA6061_AA2024 materials [12]. In this work, an attempt is made to join 5 mm-thick aluminum alloys AA5083-H321 and AA6061-T6 using FSW and investigate the effect of welding speed on the tensile strength and microstructure of the dissimilar joints.

II. EXPERIMENTAL

A FSW tool made of H13steel having cylindrical taper threaded pin profile and with scrolled surface concave shoulder was used to weld the alloys. The tool had a shoulder diameter of 18 mm, pin diameter of 6 mm and pin length of 4.7 mm. The FSW tool was manufactured using CNC turning center and wire cut EDM machine to get a exact profile. The tool was oil hardened to 55HRC. Aluminum alloys AA5083-H321 and AA6061-T6 were used in this work. Their chemical composition is shown in Table 1. Plates with dimensions of 200 mm×75 mm × 5 mm were prepared from the rolled plates. AA5083-H321 and AA6061-T6 alloys were respectively kept on the advancing side and retreating side of the joint line. The FSW line was perpendicular to the rolling direction of AA5083-H321 and parallel to the rolling direction of AA6061-T6. The dissimilar butt welding was completed on a vertical milling machine. Four joints were fabricated at four different welding speeds of 40, 63,80 and 100 mm/min. The rotational speed and tool tilt angle were kept as 1120 r/min and 2.5^0. Schematic draw of the weld joint and tool is as shown in Fig.2. A non-consumable H-13 tool steel with concave shoulder and scrolling on the shoulder surface is chosen as tool material to fabricate the joints, due to its high strength at elevated temperature, thermal fatigue resistance, and low wear. The diameter of the shoulder and pin used were 18mm, 6mm respectively and length of the pin is 4.7 mm with taper cylindrical threaded tool pin profile is used to weld. After the welding process, the joints were visually inspected for exterior defects and it was found that the joints were free from any external defects. The butted plates were clamped on a steel backing plate. The welding tool is tilted by 2.5 degrees of angle with reference to the welded plates and tool was rotated in the clockwise direction. A constant axial force is applied to all the joints. A specimen was cut from the welded plate perpendicular to the FSW line to carry out the microstructural characterization. The test sample was prepared according to the standard metallographic procedure and etched with modified Keller reagent. The computerized picture of the macrostructure of the etched specimen was captured utilizing a digital optical scanner. The microstructure was seen utilizing an optical microscope and scanning electron microscope. The tensile samples were prepared according to ASTM E8 norms. Two such tensile specimens were prepared and the average ultimate tensile strength (UTS) was taken. The UTS was evaluated utilizing a computerized universal testing machine. The broken specimen of the maximum tensile strength was seen using a scanning electron microscope. Specimens for impact testing were taken in transverse to the weld direction and machined according to ASTM A370 norms. The charpy "V" notch impact test was carried out at room temperature utilizing pendulum type impact testing machine. The amount of energy absorbed in fracture was recorded and the absorbed energy is defined as the impact toughness of the material. The Schematic draw of impact and tensile specimens was shown in Fig.1. Specimens were cut at the center of the joints in the transverse direction to conduct microhardness study. Microhardness test was completed utilizing Vickers digital microhardness tester with a 500 g load for 10 s duration. The microhardness was measured at an interval of 3 mm over the WZ, Thermo-Mechanical Affected Zone (TMAZ), Heat-Affected Zone (HAZ) and (base metal) BM. The joints made with tool rotation speed at 1120rpm, tool tilt angle 2.5^0 and weld speed at 80 mm/min resulted in good mechanical properties as compared with other weld conditions due to adequate heat generation and proper mixing of the material in the weld zone.

Table.1: Chemical composition of parent materials (mass fraction, %)

Alloy	Mg	Mn	Cu	Cr	Si	Fe	Al
AA6061-T6	1.046	0.101	0.259	0.195	0.533	0.262	Bal
AA5083-H321	4.0	0.548	0.065	0.10	0.145	0.238	Bal

Table.2: Mechanical properties of parent materials.

Alloy	Yield strength Mpa	Ultimate tensile strength Mpa	% of Elongation mm	Average hardness at 0.5kg load (VHN)	Impact strength (J)
AA6061-T6	283	353	18	120	8
AA5083-H321	238	311	20	96	16

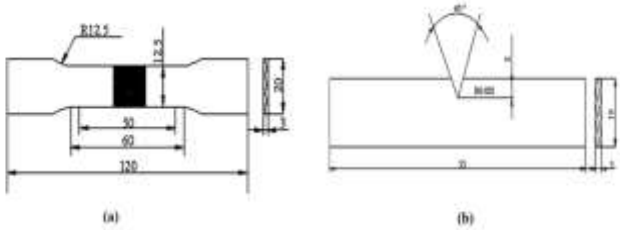

Fig.1: Schematic Sketch of (a) Tensile Specimen (b) Impact Specimen.

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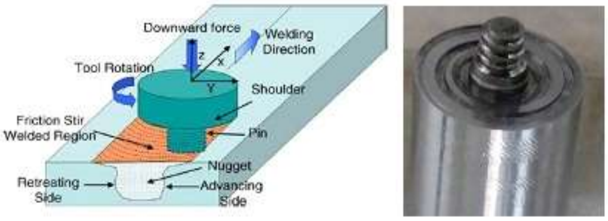

Fig.2: Schematic Sketch of Friction Stir welding showing the Various Characteristic Regions and tool

III. RESULTS AND DISCUSSION

FSW of 5 mm-thick aluminum alloys AA5083-H321 and AA6061-T6 were accomplished. The flow stresses of the two aluminum alloys are distinctive. Aluminum alloy AA5083 offers more resistance to plastic flow compared with AA6061 [13]. The rubbing of the FSW tool shoulder on the plates forms such features which are known as the wake effect [14]. It is clear that the joint has no defects such as piping or worm hole, tunnels. The macrostructure recommends that the sufficient frictional heat is formed at the chosen parameters to

1. Microstructure Studies

In conventional welding of aluminum alloys, the defects like slag inclusion, porosity, solidification on crack, and so on decreases the weld joint properties and weld quality. Notwithstanding, utilizing FSW the joints are free from these imperfections since there is no melting occurs during the welding and metals are bonded in the solid state itself because of the heat produced by the friction and flow of the metal affected by the stirring activity. The samples for metallographic examination were cut to the required size from the FSW joints transverse to the welding direction, polished and then etched with a solution of **Keller's reagent** - 2ml HF (48%) + 3ml HCl + 5ml HNO3 + 190ml H2O. This etchant gives the possibility to reveal grain boundary complexity and precipitates in several wrought alloys. The etchant reveals that AA5083 is lighter and AA6061 is darker in colour. The microstructural changes from the weld zone to the unaffected base metal were examined with optical microscopy. The microstructure of the friction stir welded aluminum alloys joint consists of different zones such as (a) stir zone (b) thermo mechanical affected zone (c) heat affected zone. The development of above zones is influenced by the material flow behaviour under the affected by welding speeds with rotating nonconsumable tool. The optical microstructure of the weld zone at various weld speeds with constant tool rotation speed and tool tilt angle are displayed in Fig.3. From the observed microstructure, the joints fabricated at the condition with the tool rotation speed of 1120rpm, weld speed of 80 mm/min and tool tilt angle of 2.5^0 observed to be having finer grains contrasted to other conditions which yielded defect free weld. This refinement is because of the dynamic recrystallization caused by simultaneously received plastic shear deformation and frictional heat [15].The plasticized dissimilar alloys are mechanically coupled to each other. The infiltration of one aluminum alloy into the other is not fully accomplished. Yet, dynamic recrystallization of grains is clear. The stirring action of the tool causes intense plastic deformation and in situ extrusion of aluminum alloys AA6061 and AA5083. The plasticized material is moved layer by layer, which structures such a lamellae structure. The penetration and mixing of both the aluminum alloys in this area is extreme. Figures 3(a) and (b) show the microstructures of the base material of AA5083 and AA6061 respectively. Different grain sizes of the stir zones are also observed in Figs.3(c)_(f). Figure 3(e) shows the stir zone composed of fine-equiaxed recrystallized grains and precipitates scattered in a finer matrix. The fine recrystallized structure at the stir zone is a high plastic deformation followed by dynamic recrystallization happening amid thermo-mechanical processing. TMAZ neighbouring the weld nugget is plastically deformed and thermally affected.

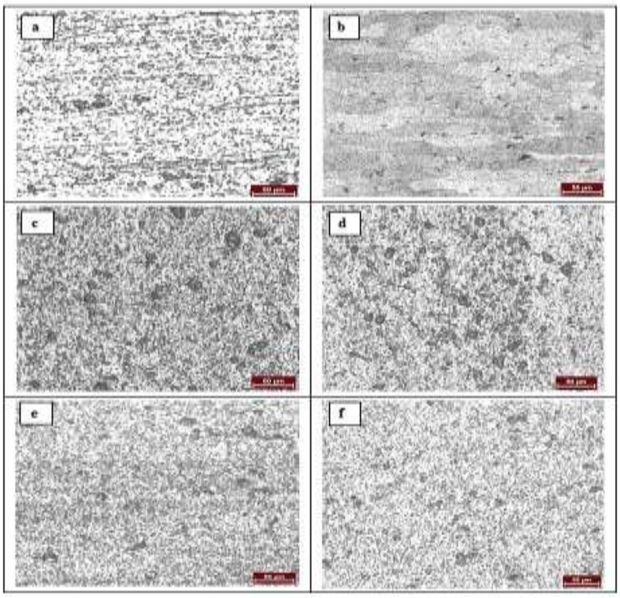

Fig.3: Microstructure of Weld Zones of FSW Joints at Various Conditions: (a) Base Metal AA5083, (b) Base Metal AA6061, (c) F1=1120 rpm, 40mm/min,2.5^0 ,(d)F2= 1120 rpm, 63 mm/min,2.5^0 and (e)F3= 1120 rpm, 80 mm/min, 2^0 (f)F4= 1120 rpm, 80 mm/min, 2.5^0

The hardness profiles assessed over the stir zone at various conditions is shown in Fig.7. The hardness of the base metal is 96HV and 120 HV. The hardness of the nugget zone is influenced by annealing softening and grain refinement in pure metals [16]. The average hardness of weld zone is found to be significantly lower than that of the hardness of the base metal. In Harries and

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Norman's work, it is recommended that the variation of the microhardness values in the welded zone and base metal is because of the difference between the microstructure of the parent metal and weld zone [17]. In any case, in the present review, the hardness of the weld zones fabricated by tool rotation speed at 1120 rpm, tool tilt angle 2.5^0 and weld speed at 80 mm/min observed to be 84Hv which is higher than that of other conditions. This is because of the presence of very finer grains at the stir zone. The weld center has bring down hardness than that of the base metal regardless of smaller grain size.

2. Mechanical Properties

Mechanical properties for example, yield strength, tensile strength and percentage of elongation have been assessed. At each condition, two samples were tested and the average of the results of two samples is presented. Table 2 shows the tensile properties of base metal and Table 3 indicates mechanical properties of the aluminum alloys weldments. From the experimental outcome, at the tool rotation speed of 1120 rpm, tool tilt angle 2.5^0 and weld speed of 80 mm/min exhibited better tensile and impact properties and the joint efficiency (58.8%) is also higher as compared to other conditions.

Table.3: Mechanical properties of weld materials.

EXP NO	UTS (MPa)	YS (MPa)	%EL (mm)	MH (VH)	IE (J)	joint efficiency %
F1(1120 rpm - 40 mm/m- 2.5^0),	175	140	6.6	75	30	56.3
F2 (1120 rpm - 63 mm/m- 2.5^0),	178	143	6.9	78	32	57.2
F3 (1120 rpm - 80 mm/m- 2.5^0),	183	150	8.2	84	34	58.8
F4 (1120 rpm - 100 mm/m- 2.5^0),	178	120	7.4	75	24	57.2

2.1. Effect of Welding Speed

The translation of tool moves the mixed material from the front to the back of the tool pin. The rate of heating of thermal cycle in FSW is a function of the welding speed. A huge increment in welding speed is accomplished with high weld quality and fabulous weld joint properties. The softened region is smaller for the higher welding speed than that for the lower welding speed. In this way, the tensile strength of aluminum alloys weldments has a proportional relationship with welding speed. The joints fabricated by tool rotation speed at 1120 rpm, tool tilt angle 2.5^0 and weld speed at 80 mm/min obtained higher tensile strength than other conditions. This is because of the intense plastic deformation and adequate frictional heat generation in the weld zone. At lower welding speed (i.e. 40 and 63mm/min) brought about higher temperature and slower cooling rate in the prepared zone causes grain development which brings about the decline in quality and hardness. The welding speed has a strong affect on productivity in streamlined generation of FSW of aluminum alloy sections. A huge increment in welding speed is achieved with high weld quality and superb joint properties. The impacts of welding speed on mechanical properties of the dissimilar joints are shown in Fig. 4-8. At the lowest (i.e. 40 and 63mm/min) and the highest (100mm/min) welding speeds, a lower tensile strength was noticed. The increment of welding speed prompts to the increment of the tensile strength up to the highest value, while additionally increase in welding speed effects in the decrease in the tensile strength of friction stir welded joints. The welding speed prompts the translation of tool, which thusly pushes the stirred material from front to the back of the tool pin and finishes the welding. The rubbing of tool shoulder and pin with the workpiece generates frictional heat. The welding speed determines the exposure time of this frictional heat per unit length of the weld and in this way influences the grain growth and precipitates. Optimum presentation time and translation of stirred material will lead to great consolidation of material with finer grains. Since joint which encounters such condition at the welding speed of 80 mm/min during welding displayed the highest UTS. The reduction in frictional heat production with an increase in welding speed was observed. Higher heat conditions prevail at lower welding speeds with slower cooling rate, which leads to coarsening of grains and dissolution of precipitates [10,18] Lower welding speeds cause uncalled for solidification of material, which leads to the reduction in UTS attributable to the defect. The mixing gets to be distinctly lacking at higher welding speeds. The material present on the advancing side of the tool does not travel enough to the retreating side, which causes a defect. Lower heat production with rapid cooling rate happens at higher welding speeds. The inclination of the tool to drag at higher welding speeds furthermore adds to the lower UTS. The welding speed impacts the plastic stream of material, change in grain size and precipitates and development of defects. The components that find the tensile strength of dissimilar aluminum alloy joints are the existence of macroscopic defects in weld zone and the level of plastic flow and amount of stirring of both the materials.

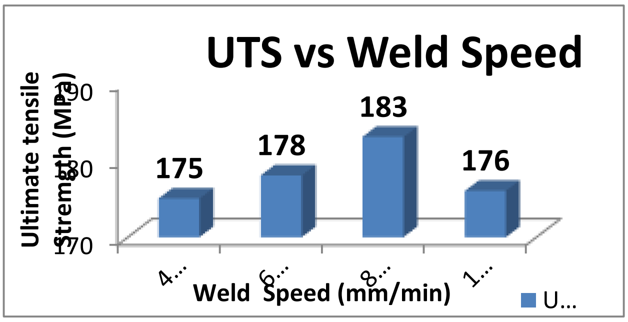

Fig.4: The effects of welding speed on ultimate tensile strength of the dissimilar joints

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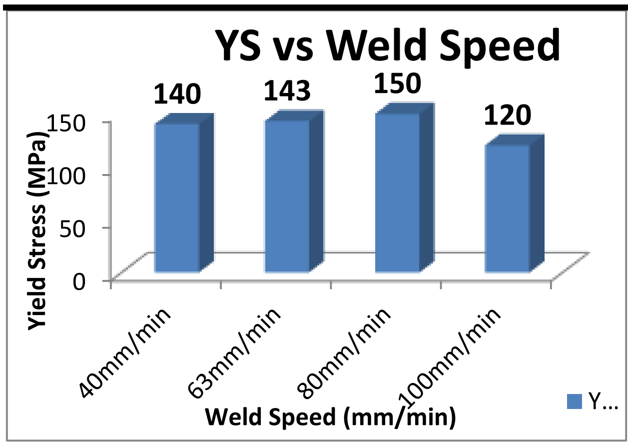

Fig.5: The effects of welding speed on the yield strength of the dissimilar joints.

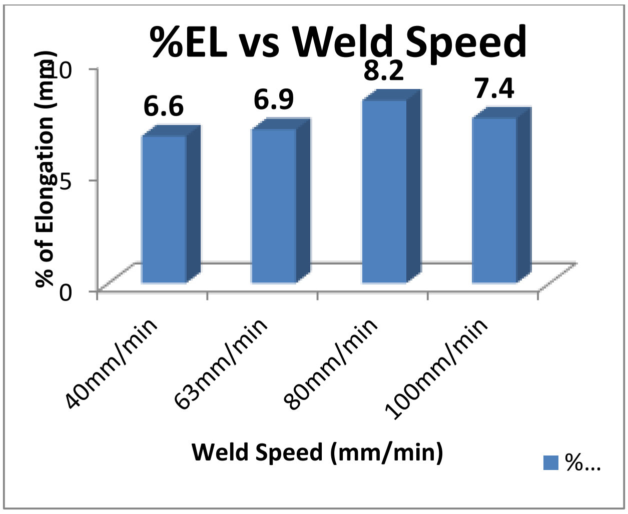

FIG 6: The effects of welding speed on % of elongation of the dissimilar joints.

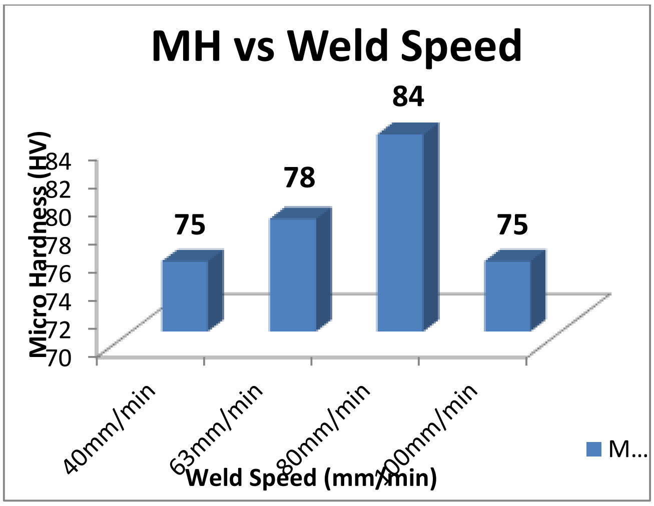

Fig.7: The effects of welding speed on microhardness of the dissimilar joints.

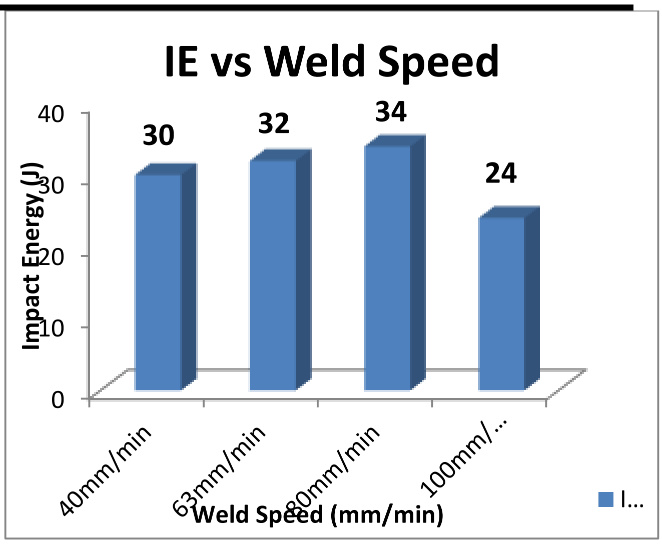

Fig.8: The effects of welding speed on impact energy of the dissimilar joints.

3. Fractography

The fractural morphology of the tensile and impact specimens of the fracture surface of the weld joints was studied utilizing the scanning electron microscopy (SEM) to understand the mode of failure. Fractured specimens of the weld joints are shown in Fig.6 and Fig.7. The dimple pattern is seen in the whole width of the specimen. All joints were failed on the retreating side during tensile testing where hardness value is least. The joints fabricated at the condition of tool rotation speed at 1120rpm, tool tilt angle 2.5^{0}and weld speed at 80 mm/min exhibited higher ductility as compared with other conditions. This is due to a presence of tiny shallow dimples and also some large dimples resulted from micro dimples coalescence. It could be credited to the high plastic deformation which shows the more intense ductile fracture.

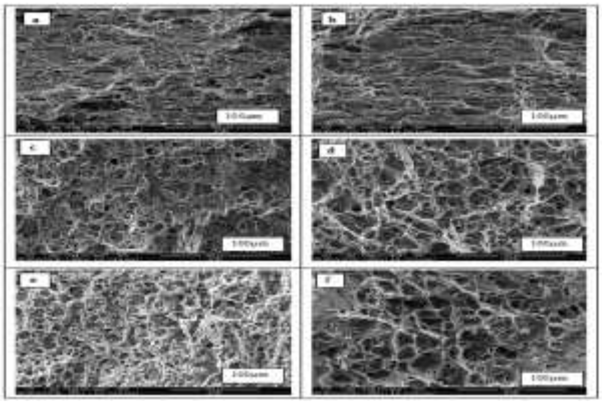

Fig.6: Tensile fracture images (a) Base AA5083 , (b) Base AA6061, (c) F1, (d) F2, (e) F3, (f) F4.

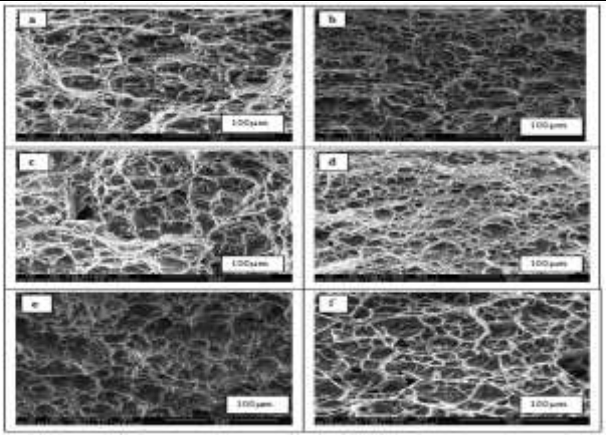

Fig.7: IMPACT fracture images (a) Base AA5083 , (b) Base AA6061, (c) F1, (d) F2, (e) F3, (f) F4.

IV. CONCLUSIONS

The mechanical properties of AA5083to AA6061weldments made by FSW were investigated. The following conclusions can be drawn. The weldments made by FSW at the tool rotation speed of 1120rpm, weld speed of 80mm/min and tool tilt angle 2.5^0 displayed better mechanical properties. This is because of adequate heat generation and proper mixing of the material in the weld zone. Further, it is additionally watched that finer grains were shaped in the weld zone which is because of dynamic recrystallization. The fracture surface of both tensile and impact specimens shows a ductile fibrous fracture at weld zone of AA5083 to AA6061weldments. The dissimilar joint shows the presence of different zones such as heat affected zone (HAZ), thermomechanically affected zone (TMAZ) and stir zone (SZ).The welding speed affects the formation of plastic flow region. The joints fabricated at the lowest or highest welding speeds show the absence of mixed flow region.

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